Prepared in cooperation with the New England Interstate Water Pollution Control Commission

Concentrations, Loads, and Yields of Total Nitrogen and Total Phosphorus in the Barnegat Bay-Little Egg Harbor Watershed, New Jersey, 1989-2011, at Multiple Spatial Scales

By Ronald J. Baker, Christine M. Wieben, Richard G. Lathrop, and Robert S. Nicholson

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Conversion Factors

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
	Area	
hectare (ha)	2.471	acre
square kilometer (km^2)	247.1	acre
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
	Application rate	
kilograms per hectare per year [(kg/ha)/yr]	0.8921	pounds per acre per year [(lb/acre)/yr]

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

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Abstract

Concentrations, loads, and yields of nutrients (total nitrogen and total phosphorus) were determined for the Barnegat Bay-Little Egg Harbor (BB-LEH) watershed for years 1989-2011 at annual and seasonal (growing and nongrowing) time scales. Concentrations, loads, and yields were determined at three spatial scales: for each of the 81 subbasins specified by 14-digit hydrologic unit codes (HUC-14s); for each of the three BB-LEH watershed segments which coincide with segmentation of the BB-LEH estuary; and for the entire BB-LEH watershed. Baseflow and runoff values were calculated separately and combined to provide total values.

Available surface-water quality data for all streams in the BB-LEH watershed for 1980-2011 were compiled from existing datasets and quality assured. Precipitation and hydrologic data were used to identify which water-quality samples were collected during base-flow conditions and which were collected during runoff conditions. Base-flow separation of hydrographs of six streams in the BB-LEH watershed indicated that base flow accounts for about 65-90 percent of total flow in streams in the watershed.

Base-flow mean concentrations (BMCs) of total nitrogen (TN) and total phosphorus (TP) for each HUC-14 subbasin were determined from relations between land use and measured base-flow concentrations. These relations were developed from multiple linear regression models determined from water-quality data collected at sampling stations in the BB-LEH watershed under base-flow conditions, and land-use percentages in the contributing drainage basins. The total watershed base-flow stream discharge was estimated for each year and season from continuous streamflow records for 1989-2011, and relations between precipitation and streamflow during base-flow conditions. For each year and season, the load and yield were then calculated for each HUC-14 subbasin from the BMCs, total base-flow volume, and land area.

The watershed-loading application PLOAD was used to calculate runoff concentrations, loads, and yields of TN and TP at the HUC-14 scale. Flow-weighted event-mean concentrations (EMCs) for runoff were developed for each major land-use type in the watershed using storm sampling data from four streams in the BB-LEH watershed and three streams outside the watershed. The EMCs were developed separately for the growing and nongrowing seasons, and were typically greater during the growing season. The EMCs, along with annual and seasonal precipitation amounts, and percent imperviousness associated with land-use types, were used as inputs to PLOAD to calculate annual and seasonal runoff concentrations, loads, and yields at the HUC-14 scale, which were subsequently aggregated for each watershed segment and for the entire watershed.

Over the period of study (1989-2011), total surface-water loads (base flow plus runoff) for the entire BB-LEH watershed for TN ranged from about 522,000 kg as N (1995) to more than 921,000 kg as N (2011). For TP, total loads for the watershed ranged from about 22,800 (1995) to 40,200 kg as P (2011). On average, the north segment accounted for about 65 percent of the annual total nitrogen and total phosphorus loads, and the central and south segments each accounted for less than 20 percent of the nutrient loads. Loads and yields were strongly associated with precipitation patterns, ensuing hydrologic conditions, and land use. Runoff loads steadily increased over time as urban development expanded in the watershed. HUC-14 subbasins with the highest yields of nutrients are primarily concentrated in the northern part of the watershed, and have the highest percentages of urban or agricultural land use. Subbasins with the lowest total nitrogen and total phosphorus yields are dominated by forest cover.

Percentages of turf (lawn) cover and non-turf cover were estimated for the watershed. Of the developed land in the watershed, nearly one quarter (24.9%) was mapped as turf cover. There is a strong relationship between percent turf and percent developed land, such that percent turf in the watershed typically increases with percent development, and turf can be considered a reasonable predictor of the amount of development in the watershed. In the BB-LEH watershed, predicted concentrations of total nitrogen and total phosphorus were greater for developed- turf areas than for developed- non-turf areas, which in turn, were greater than those for undeveloped areas.

Introduction

The coastal areas of New Jersey include some of the most economically and ecologically valuable resources in the state. Barnegat Bay, Manahawkin Bay, and Little Egg Harbor (fig. 1) together make up the Barnegat Bay-Little Egg Harbor (BB-LEH) estuary, a shallow, lagoonal-type estuary located along the central coast of New Jersey, separated from the Atlantic Ocean by a narrow complex of barrier islands (Kennish, 2001). Historically, the estuary has been a vital economic and recreational resource, supporting both commercial and recreational fish and shellfish industries, as well as boating and tourism. The estuary and adjacent lands offer a variety of ecologically important habitats including sand beaches and dunes, salt marshes, submerged aquatic vegetation beds, shellfish beds, and waterfowl nesting grounds (Barnegat Bay National Estuary Program, 2002).

The ecological health of the estuary has deteriorated over the last few decades (Kennish and others, 2007), and the estuary has been classified as a highly eutrophic system based on application of NOAA's National Estuarine Eutrophication Assessment model (Bricker and others, 2007) and Nixon's (1995) trophic classification. Human population is increasing rapidly in the watershed, accompanied by increasing urban development and other changes in land use; therefore, understanding the effects of land-use alteration on the estuary is becoming increasingly important. In particular, the role of nutrient (nitrogen and phosphorus) loading from the watershed on the eutrophication of this coastal estuary must be better understood if further environmental degradation is to be avoided.

The estuary has experienced increases in macroalgal growth, harmful algal blooms, and turbidity, as well as oxygen depletion, declines in harvestable fisheries, and changes in species composition, including decreases in the biomass and size of seagrass beds (Kennish and others, 2007). For example, Fertig and others (2013) observed a decline in eelgrass biomass in the estuary from 2004 to 2010. Low dissolved oxygen concentrations (less than 4mg/L) also have been observed in the northern and central portions of the estuary (Barnegat Bay Partnership, 2011). Harmful algal blooms (HABs) have occurred in the BB-LEH estuary as early as 1995 and as recently as 2010 (Olsen and Mahoney, 2001; Barnegat Bay Partnership, 2011). All of these conditions can be caused or exacerbated by nutrient loading from the watershed.

Harmful algal blooms (HABs) release toxins, alter water chemistry, and produce excessive amounts of biomass that interfere with normal food chains, all of which are detrimental to other organisms. Relations between estuarine eutrophication, HABs, and nutrient contributions from watersheds are well established (Heisler and others, 2008). Increased nutrient loads promote development and persistence of many HABs, and the composition, not just the total quantity, of the nutrient pool affects HABs. An exogenous source of nutrients (chronic or episodic) is required to sustain high-biomass blooms, and this can be provided by nutrient loading from the watershed. Additionally, management of nutrient inputs to the watershed can lead to significant reduction in HABs.

An understanding of nutrient cycling, from atmospheric and watershed contributions to biotic uptake and degradation, and sediment processes, is needed to fully comprehend and manage the occurrence and intensity of HABs, maintain dissolved oxygen concentrations above critical levels, and avoid depletion and loss of commercially, recreationally, and ecologically important species. In this investigation, nutrient loading from the watershed to the estuary is estimated, based on relations between land use and abundance (concentrations, loads, and yields) of nitrogen and phosphorus in streams that discharge to the estuary. Temporal and spatial variability of nutrient loading, as a function of stream location, season, meteorology, and upstream land use are considered. Available hydrologic, water-quality, precipitation, and land-use data were compiled and used in conjunction with a watershed loading application to determine nutrient loading rates on several spatial scales: for each of the 81 subbasins specified by 14-digit hydrologic unit codes (HUC-14s); for each of the three BB-LEH watershed segments; and for the entire BB-LEH watershed.

Figure 1. The Barnegat Bay-Little Egg Harbor estuary and watershed, New Jersey.

Purpose and Scope

The purpose of this investigation was to document the influence of changes in land use on past and present nutrient export from the BB-LEH watershed to the BB-LEH estuary, and quantify the spatial and temporal loading of nutrients. The objectives were to develop more detailed nutrient loading estimates for the BB-LEH watershed than have been reported in past studies, to evaluate the contributions of lawn-care products to nutrient loading by quantifying and relating turf coverage to nutrient concentrations and loads, and to quantify runoff loading separately from base-flow loading so that a baseline assessment of how well stormwater management systems are currently performing could be observed.

Physical and chemical watershed data and land-use patterns were used to quantify loading of total nitrogen (TN) and total phosphorus (TP) from the watershed to the estuary. Concentrations, loads, and yields of TN and TP were determined for years 1989-2011. Loads were calculated on an annual and seasonal (growing and nongrowing) basis. Base-flow loads were calculated directly from precipitation, hydrologic, and water-quality data, whereas PLOAD, Version 3.0 (U.S. Environmental Protections Agency, 2001) was used to estimate runoff loads of nutrients.

Description of Study Area

The BB-LEH watershed covers approximately 1,445 km^2 and the estuary covers an additional 279 km^2. The watershed lies entirely in the Atlantic Coastal Plain physiographic province, and includes the drainage basins of numerous streams and their tributaries that discharge to the BB-LEH estuary. From north to south, the major streams that discharge to the BB-LEH estuary are the Metedeconk River, Toms River, Cedar Creek, Forked River, Oyster Creek, Mill Creek, Cedar Run, Westecunk Creek, and Tuckerton Creek (fig. 1).

For this report, the watershed was divided into three segments—north, central, and south—to coincide with the natural segmentation of the estuary (Michael Kennish, Rutgers University, oral commun., 2011) (fig. 2). The north segment of the watershed covers 801.4 km^2 and contains the drainage basins for the Metedeconk and Toms Rivers. The central segment covers 351.6 km^2 and contains the drainage basins for Cedar Creek, Forked River, and Oyster Creek. The south segment covers 291.6 km^2 and contains the drainage basins for Mill Creek, Cedar Run, Westecunk Creek, and Tuckerton Creek.

Figure 2. Northern, central, and southern segments of the Barnegat Bay-Little Egg Harbor estuary and corresponding watershed segments and subwatershed boundaries.

Predominant land uses in the BB-LEH watershed vary regionally (fig. 3). The northeastern mainland area is highly developed with both residential and non-residential development, and includes major population centers such as Toms River and Lakewood. The southeastern mainland area contains several protected wildlife refuge and wildlife management areas and is less heavily developed than the northeastern portion of the watershed; however, this area has undergone a substantial increase in development in recent years. The complex of barrier islands on the eastern shore of the estuary is heavily developed, with the exception of Island Beach State Park. Much of the western portion of the watershed lies in the Pinelands National Reserve (PNR); this area is protected under the Pinelands Comprehensive Management Plan and is characterized by large tracts of forested land and some low-density development (Kennish, 2001; Hunchak-Kariouk and Nicholson, 2001).

Figure 3. Land-use in the Barnegat Bay-Little Egg Harbor watershed, 1986, 1995, 2002, 2007.

The BB-LEH watershed contains 81 subbasins at the Hydrologic Unit Code (HUC)-14 scale. The percentage of land in each land-use category was quantified for each of the HUC-14 areas for 1986, 1995, 2002, and 2007, based on land-use/land-cover digital datasets produced by the New Jersey Department of Environmental Protection (1986, 2001, 2008, 2010) (table 1). The land-use classification system for each of the digital datasets is derived from Anderson and others (1976). For this report, residential urban land was distinguished from nonresidential urban land (commercial, industrial, and military installations). Additionally, some transportation-related areas such as major roadways and airport facilities were classified as impervious urban.

Table 1. Land-use distributions for subbasins at the HUC14 scale in the BB-LEH watershed for 1986, 1995, 2002, and 2007 land-use years.

Since the land-use survey of 1986, the amount of urban land has increased with each successive survey, accompanied by a decrease in forested and agricultural land. Between the 1986 and 2007 land-use surveys, urban land increased within the watershed from 21.7 to 30.2%, forested land decreased from 45.7 to 39.1%, and agricultural land decreased from 2.0 to 1.2%.

In addition to being the largest of the three watershed segments, as of 2007, the north segment had the highest percentage of urban land cover (39.3%, of which 28.9% is residential, 9.8% is nonresidential, and 0.6% is impervious), and the lowest percentage of forested land cover (33.9%) (table 2). In comparison, the south segment is the smallest and is comprised of 21.9% urban and 40.1% forested land covers. The central segment is the least developed, with 16.4% urban and 50.1% forested land covers.

Table 2. Land-use distributions for segments of the Barnegat Bay-Little Egg Harbor watershed.

Previous Studies

A profile of Barnegat Bay (Rogers, Golden and Halpern, Inc., 1990) was prepared from publications and other secondary sources to report the nature and extent of development effects on Barnegat Bay. Tidal data, estimated bay water volume, and published reports were used in that report to summarize bathymetry, turnover time, and circulation. Sediment deposition rates and characteristics, and water quality were reported. Nitrogen was identified as the limiting nutrient and concentrations were generally higher north of Barnegat inlet than in the southern portion of the Bay according to that report. A general lack of nutrient data, especially in the estuary, was noted, but available watershed nutrient data indicated that nitrogen loading from undeveloped areas was lower than from agricultural and urban areas. Additional urbanization of the watershed was stated as the greatest threat to the health of the Bay in that report.

Upgrading or removal of domestic wastewater treatment plants from streams has reduced nutrient loads to streams in estuaries, particularly in the 1970s-80s. Hickman and Barringer (1999) studied changes in water quality of streams throughout New Jersey during the period 1986-95. They observed that more streams showed decreasing rather than increasing trends in reduced forms of nitrogen (organic nitrogen and ammonia) and total nitrogen concentrations, but that nitrate plus nitrite concentrations tended to increase with time. Those trends are consistent with treatment plant removal and upgrades being associated with decreases in TN loads, but some upgrades result in a portion of the ammonia and organic nitrogen being oxidized and released as nitrate (which can increase nitrate loads). In a follow-up study for the years 1998-2007 (Hickman and Gray, 2010), decreasing trends in organic nitrogen plus ammonia were reported for six stations, and increasing trends were reported for nine. Decreasing trends for nitrate plus nitrite occurred at four stations, whereas increasing trends occurred at 19 stations (including Toms and Metedeconk Rivers). From these observations it appears as though, throughout New Jersey, the decreasing trend in reduced nitrogen caused by treatment plant decommissioning and upgrades has leveled off, with nitrate plus nitrite concentrations continuing to increase. For the BB-LEH watershed, where treatment plants have been removed (not upgraded), nutrient loads, including nitrate, would have been expected to decrease. Therefore, the observed trend in increasing nitrate loading is likely the result of other factors related to increased development.

A report of the environmental and ecological conditions of Barnegat Bay in 2011 (Barnegat Bay Partnership, 2011) identified development in the watershed as an important contributing cause of environmental degradation of this resource. Substantial increases in urban development and decreases in wetland areas during the previous decade were indicated as being problematic with respect to the environmental health of Barnegat Bay. Also noted in that report was a progressive decline in many environmental indicators and important species, including shellfish, sea grass, and threatened and endangered species. Analysis of 1995 land use patterns (Lathrop and Conway, 2001) showed that about 25 percent of the BB-LEH watershed was urban, and another 27 percent was available for development at that time. If the complete build-out scenario were to be eventually implemented, nutrient loading attributable to urban land use could increase substantially. In addition, increase of impervious surface throughout the watershed will affect water quality and hydrologic characteristics of many streams in the watershed (Schueler, 1994).

Hunchak-Kariouk and Nicholson (2001) quantified the watershed contributions of nutrients to the BB-LEH estuary. Using available hydrologic, water-quality and atmospheric-deposition data, they calculated loading of TN, TP, and dissolved nitrogen and phosphorus species during high- and low-flow conditions at 25 sampling locations in the BB-LEH watershed. They noted an increasing trend in nutrient loading with increasing land development. Median TN and TP concentrations in basins with less than 10 percent urban land (Landscape I) were about half those with greater than 10 percent urban land use (Landscape II). Median values for nitrate plus nitrite were even more divergent: 0.02 mg/L as N for Landscape I, 0.36 mg/L as N for Landscape II. Median TN concentrations at individual sites were higher in the northern portion of the watershed, corresponding to areas with the greatest percents of urban land use. Atmospheric deposition of nitrogen directly to the estuary was credited with 34 percent of the total load, 54 percent was from surface-water sources, and 12 percent was from direct groundwater discharge to the estuary in that report.

Velinsky and others (2011) investigated the historical intensity and effects of nutrient loading to Barnegat Bay by characterizing and measuring the rates of sediment deposition in the tidal marshes, which ranged from 0.14 to 0.30 cm/yr. They noted an decrease in the concentration of nitrogen, and to a lesser extent phosphorus, with sediment depth. The sediment record indicated that the increase in loading leading to the increase in sediment concentrations began in or around the 1950s. This report showed that the bay marshes can sequester a significant amount of nutrient mass into the bottom sediment that would otherwise flow into the estuary, and that the total loads of nutrients that flow through these wetlands has increased with time.

Baker and Hunchak-Kariouk (2006) quantified runoff and base-flow loading of nutrients to four tributaries of the Toms River, which terminates in the northern portion of Barnegat Bay, from 1994-99. They reported a strong correlation between nonpoint-source nutrient loading from runoff and urban development. Two streams in the highly and moderately developed basins had substantially higher nutrient concentrations and loads than two streams in lightly developed and undeveloped basins. A study of six tributaries to the Lower Delaware River from 2002-07 identified agricultural land use, largely absent in the BB-LEH watershed as the most significant factor in nutrient loading (Baker and Esralew, 2010). Concentrations and loads of nitrogen and phosphorus were highest in the two agricultural basins (Alloway Creek—characterized by intense cattle production, and Blacks Creek—dominated by row crops), followed by the two urban basins (Timber Creek and Cooper River). The Cooper River basin is highly urbanized, largely with older developments. A legacy of several sewage treatment plants that operated for many decades on the Cooper River and have recently been removed are likely responsible for the high loads of phosphorus, which are continuously released from the sediments during high flow and runoff events. Loading of all nutrient species was generally lowest for the two streams in undeveloped basins (Lahaway Creek tributary and Gravelly Run).

Water quality and other characteristics of the North branch of the Metedeconk River, Cedar, Mill and Westecunk Creeks were monitored during a study of Diamondback Terrapins (Malaclemys terrapin) in Barnegat Bay as an indicator of local contamination in estuarine environments (Basile, 2010). Higher concentrations of nitrogen species were recorded in samples collected from the Metedeconk River, a highly developed basin, than in the three creeks, all of which are located in basins with lesser urban development. Nitrogen concentrations were generally higher during the growing season compared to the nongrowing season, and were lower during runoff events due to dilution from precipitation.

Gao (2002) monitored atmospheric deposition rates of nitrate and ammonia in precipitation (wet deposition) and aerosol particulates (dry deposition) at Tuckerton, NJ, near the southern end of Barnegat Bay, in 1999 and 2001. Wet deposition accounted for greater than 88 percent of total nitrogen deposition. Nitrogen deposition rates were highest in the summers, corresponding with the growing season. The annual atmospheric nitrogen contribution to Barnegat Bay from atmospheric sources (nitrate plus ammonia) was estimated to be 1.5×10^7 moles per year. Gao and others (2007) also compared deposition rates at the Tuckerton, NJ site to those at a Northern New Jersey atmospheric deposition station (Sandy Hook, NJ). Rates were higher at the northern site (mean nitrate plus ammonia concentration, 70.9 μmol/L) than at Tuckerton (47.4 μmol/L, which is consistent with more intense anthropogenic nitrogen sources in the highly developed north compared to the less developed south areas of the New Jersey coast. Nitrate concentrations in the Mullica River-Great Bay estuaries were lowest during the summer, when biotic uptake is greatest, and ammonia concentrations were greatest in the fall (Gao and others, 2007).

Methods

A combination of existing data and estimation methods was used to calculate TN and TP concentrations, loads, and yields. If sufficient water-quality and hydrologic data had been available to characterize these parameters annually and seasonally, then loads and yields for the desired spatial and temporal increments could have been calculated directly. Lack of sufficient, however, necessitated the use of multiple linear regression models relating land use and water quality to calculate base-flow loading, and the use of PLOAD to calculate runoff loading.

Determining concentrations, loads, and yields of TN and total phosphorus required quantification of streamflow under runoff and base-flow conditions. Days when streams received direct runoff were distinguished from days in which only base flow, from groundwater discharge into streams, was present. Available hydrologic and precipitation data were used in conjunction with base-flow separation procedures (to distinguish the base-flow portion of a hydrograph from the runoff portion) to determine annual and seasonal (growing, nongrowing) base-flow and runoff volumes for 1989-2011 for the entire study area and for each HUC-14 subbasin. The dates of the growing season, April 1 to October 31, and nongrowing season, November 1 to March 31, were based on the average dates of the first and final frosts in New Jersey (Ruffner and Bair, 1977).

Principal land-use categories considered for this study are: agriculture, barren, forest, impervious urban, residential urban, nonresidential urban, water, and wetland. The percentage of land in each land-use category for each HUC-14 subbasin was determined using digital geodatasets for years 1986, 1995, 2002, and 2007. These years are hereafter referred to as “land-use years”. Each year of water-quality data collection from 1989-2011 was assigned land-use percentages from the closest land-use year. For example, water-quality data collected from 1999-2004 was related to land-use percentages from 2002, whereas data collected from 2005-2011 was related to land-use percentages from 2007. For the purpose of this report, “land-use period” refers to the range of years that corresponds to a given land-use year.

Concentrations, loads, and yields of TN and TP were calculated on an annual and seasonal basis with the use of water-quality data and relations between concentrations and land-use percentages for base-flow conditions, and the use of PLOAD for runoff conditions. Concentrations are reported as milligrams per liter (mg/L), loads are reported as kilograms (kg), and yields (area-normalized loads) are reported as kilograms per hectare (kg/ha).

Water Budgets

Land-surface and groundwater-based water budgets can be used to calculate runoff and base-flow values (Gray, 1970; Charles and others, 2001; Gordon, 2004; Walker and others, 2011). The land-surface-based water budget can be expressed as:

$$P + D_{as} \pm \Delta S_{sw} \pm \Delta S_{sm} = Q_{dr} + ET + W_s + R_s$$

(1)

where

- P = precipitation,
- D_{as} = artificial discharge to surface-water bodies,
- ΔS_{sw} = change in surface-water storage,
- ΔS_{sm} = change in soil-moisture storage,
- Q_{dr} = direct runoff,
- ET = evapotranspiration,
- W_s = surface-water withdrawals/diversions, and
- R_s = recharge to the aquifer system

This relation can be simplified by eliminating terms that do not substantially affect the water budget of the BB-LEH watershed. Little change in storage (ΔS_{sw} and ΔS_{sm}) is expected over a seasonal or annual time scale. Gordon (2004) determined that W_s (0.019”) and D_{as} (0.114”) represented a minor fraction of precipitation (44.7”) in a study of the hydrology of the Forked River, Cedar Creek, Mill

Creek, Westecunk Creek, Tuckerton Creek, and other basins in and near the BB-LEH watershed for years 1998-99. Therefore, the land-surface-based water budget can be simplified to:

$$P \approx Q_{dr} + ET + R_s \qquad (2)$$

The groundwater-based water budget can be expressed as:

$$R_g + D_{ag} \pm R_i = Q_b + W_g \pm L \pm \Delta S_{gw} \qquad (3)$$

where

R_g = recharge to the aquifer system,

D_{ag} = artificial discharge to the aquifer system,

R_i = groundwater inflow to/outflow from adjacent basins,

Q_b = base flow,

W_g = groundwater withdrawals,

L = leakage to confined aquifers, and

ΔS_{gw} = change in groundwater storage.

The relation in equation 3 also can be simplified by assuming no substantial change in storage (ΔS_{gw}) and no substantial effect on surface-water flows from artificial discharge to the aquifer system (D_{ag}), which was calculated to be 0.125" in the study area of Gordon (2004). Leakage to confined aquifers (L) also was minor (0.22"). Groundwater withdrawal for each county in New Jersey was quantified by Hoffman (2000). The average Ocean County withdrawal from surficial aquifers from 1990-96 was 0.27 in., which is equivalent to about 0.6% of the average precipitation over that period

(44.86 in.). Therefore, W_g can be neglected in the water budget. Groundwater inflows from adjacent basins (R_i) were assumed to be negligible for the BB-LEH watershed. However, as a result of an overlap between the groundwater and surface water divides of the Oswego and Oyster Creek basins, a portion of recharge in the Oswego River basin is discharged into the Oyster Creek basin (Gordon, 2004). In addition, groundwater discharge to Oyster Creek exceeds precipitation, and therefore a source of flow in addition to precipitation must be present. Therefore, streamflow data from the Oyster Creek gaging station were excluded from hydrologic calculations. The groundwater-based water-budget equations can then be simplified to:

$$Q_b = R_g \tag{4}$$

And, because R_s and R_g are two expressions of groundwater recharge (equivalent terms of the two water-budget relations), (2) and (4) can be combined:

$$Q_{dr} + Q_b \approx P - ET \tag{5}$$

The important assumptions here are that there is no net change in storage in the unsaturated zone or aquifer over the time period considered, that withdrawals and artificial discharges to the streams are not substantial compared to the flow terms, that net loss to or gain from adjacent basins in not substantial (except in the case of Oyster Creek), and that virtually all recharged water is discharged back to the stream upstream from the gage.

Acquisition, Screening, and Management of Water-Quality Data

To optimize the accuracy of loading estimates, all available water-quality data of suitable quality for all sampling locations in BB-LEH watershed were assembled in a database for use in load calculations. Available surface-water-quality data for all streams in the BB-LEH watershed for 1980-2011 were compiled from the USGS's NWIS database, and from the USEPA's STORET database which contains data collected by state and local agencies including the New Jersey Department of Environmental Protection, Brick Township Municipal Utilities Authority, and the New Jersey Pinelands Commission. Data for total nitrogen (TN) and total phosphorus (TP) were evaluated. A series of quality-assurance measures were taken to ensure accuracy and compatibility among data collected by the different agencies. For example, the same site was often used by multiple agencies, but there were slight differences in the name of those sites and reported coordinates. A Geographic Information System (GIS) was used to verify site locations and account for redundancy. Duplicate data among the databases were eliminated. Additionally, conversion factors were applied such that units of concentration were consistent (mg/L as N or P).

Additional steps were taken to evaluate the data for applicability to current conditions, and to check for outliers. Although it was important to utilize as much data as possible, it was equally important to use data that were representative of the period of interest, 1989-2011. Data applicability may be an issue for older data because relations between land use and nutrient concentrations in streams may change over time if the sources of contaminants change. During the 1970s, three regional wastewater treatment facilities were constructed to treat domestic wastewater from Ocean County and surrounding areas and transport the secondary effluent to the ocean more than one mile offshore (Ocean County Utilities Authority, 2013), which removed most wastewater point sources from the BB-LEH watershed. By 1980, nearly all domestic-wastewater discharges were removed from streams in the watershed. A decrease in nutrient concentrations and loads was evident after these point sources were removed. Therefore, data collected prior to 1980 were not used in this investigation.

Although the period of interest in this investigation is 1989-2011, water-quality and hydrologic data collected from years 1980 through 1988 also were considered for inclusion in the analysis. The decision as to whether or not to include data collected before 1989 was addressed separately for nitrogen and phosphorus. For TN, 1980s data were included because there was no apparent decline in mean concentration from the 1980s to subsequent decades, indicating that the effects of sewage treatment plants did not persist into the 1980s. Nitrogen data from 1980 to 2011 (corresponding to the 1986, 1995, 2002, and 2007 land-use years) were used to calculate TN loads. Variability of TP concentrations in the watershed was much greater, with more occurrences of high concentrations, during the 1980s than during subsequent years. It is likely that decades of sewage treatment plant operation continued to affect phosphorus concentrations as phosphorus associated with sediment is released into the water column over time. Only phosphorus data from 1991-2011 (corresponding to the 1995, 2002, and 2007 land-use years) were used to calculate TP loads.

The dataset was examined for outliers, and unreasonably high values, considered to be errors, were not used in the analysis. These values were identified first by visually inspecting the data for extreme values, and then by using the Discordance Test (U.S. Environmental Protection Agency, 2006). The Discordance Test quantifies the number of standard deviations from the mean for the most extreme data values. The null hypothesis is that the value in question is a member of the population being examined, and this is confirmed with a 95% certainty if the value falls within two standard deviations of the population mean. This test was applied separately to TN and TP data for each water-quality site to identify potential outliers. Each potential outlier was then examined and either rejected as an errant value that does not represent a true value, or accepted as a reasonable concentration.

Censored data also were reviewed and accounted for in the load estimations. Reporting levels of nutrient species vary according to analytical method applied, and generally decrease over time. For TN, there were 87 censored values out of 1,100 measurements for 1980-2011. These censored values were found only in data retrieved from the USGS' NWIS database, and are the result of the analytical method used to determine TN concentrations for USGS water-quality samples. The USGS uses a summation method in which nitrate plus nitrite is analyzed separately from ammonia plus organic nitrogen; nitrogen from the two methods is summed to obtain total nitrogen for the sample. By convention, if either ammonia plus organic nitrogen (as N) or nitrate plus nitrite (as N) is below the reporting level, the calculated TN value also is reported as less than that reporting level plus the value of the detected parameter. To address the need for an actual TN value for load calculations, values were assigned for the censored data. This was done by calculating the mean of all detected values less than each reporting level for which there were censored data. The resultant means were then substituted for the corresponding censored values, and added to the value of the detected parameter. This method gives more representative values than other methods such as considering nondetects to be zero, or equal to the reporting level, or equal to some fraction (commonly half) of the reporting level.

For TP, there were 154 censored values out of 817 measurements for 1991-2011. Censored TP values were found in data retrieved from both NWIS and STORET. Similar to the process for TN, values were assigned for the censored TP data. The mean values of all detected values less than each reporting level were used as the TP concentrations for the censored data associated with the corresponding reporting levels.

Determination of Sample Flow Condition

Flow conditions during each calendar day for each water-quality-sampling site were needed to distinguish samples collected during base-flow, runoff, and base-flow plus runoff conditions. This determination was based on site location, area of the drainage basin upstream of the sampling site, and daily average precipitation totals prior to sample collection.

The sampling sites were designated “North or “South”, signifying whether they are located in the northern or southern half of the watershed. Precipitation data from weather stations were similarly divided into north and south, and the appropriate precipitation data were used to determine the flow condition under which each sample had been collected.

“Baseflow days” for a stream-sampling site were defined as days in which less than 0.2 inches of precipitation had fallen during the previous number of days (N) required by the stream to return to baseflow conditions after a precipitation event. Values of N varied from 2-4 days, depending upon the basin area. A method for calculating N reported by Linsley and others (1958) (equation 1) was used:

$$N = A^{0.2} \tag{1}$$

where N is the number of days after the peak of the previous precipitation event, and A is the basin area in acres. The value of N was rounded up to the next highest number of days and an additional day was added to give a conservative assignment of base-flow day. “Runoff days” were defined as days in which greater than 0.75 inches of precipitation had occurred during the previous N days. “Base-flow plus runoff days” were days in which greater than 0.2 inches but less than 0.75 inches of precipitation had occurred.

By applying Equation 1 as described, each water-quality sample was designated as “base flow”, “runoff”, or “base flow plus runoff”. Only base-flow water-quality data were used for quantifying base-flow concentrations, loads and yields for the watershed, and only runoff water-quality data were used to quantify runoff concentrations, loads and yields.

Base-Flow Nutrient Load Calculation

Base-Flow Load Calculation

Base-flow concentrations, loads, and yields were determined at the HUC-14 level. This determination required four categories of data: daily precipitation from weather stations in or near the BB-LEH watershed; hydrologic data from continuous streamflow gaging stations; water-quality data collected during base-flow conditions from streams in the watershed; and information about basins in the watershed, including area and land-use percentages. As described in the following sections, precipitation and hydrologic data were used to identify which water-quality data were collected during base-flow conditions. Water-quality data were then related to land-use percentages to develop relations which were used for calculating base-flow mean concentrations (BMCs) of TN and TP at the HUC-14 level. BMCs were then used in conjunction with hydrologic data to calculate annual and seasonal loads and yields at the HUC-14 level. Loads were aggregated at the watershed segment and entire watershed scales.

Daily Precipitation

A subset of water-quality data with samples collected only under base-flow conditions was needed to complete the base-flow loading estimate. Because streamflow data were not always collected coincident with water-quality samples, precipitation records were used to determine which water-quality samples were collected under base-flow conditions. To account for spatial and temporal variability of precipitation, and to account for data gaps among stations, daily precipitation data for nine stations in and near the watershed (fig. 4) were retrieved from the Office of the New Jersey State Climatologist (2013) and from the National Oceanic and Atmospheric Administration's National Climatic Data Center (2013). Daily average precipitation amounts calculated from the northern stations were applied to base-flow calculations for the northern half of the watershed, and daily average precipitation amounts from the southern stations were applied to base-flow calculations for the southern half of the watershed. Data from the Indian Mills station were used in precipitation calculations for both the north and the south because of its central location. Daily average precipitation amounts for both the northern and southern halves of the watershed were calculated for the period of 1989-2011. Based on geographic location (north or south), size of the drainage basin above a water-quality sampling site, and daily average precipitation amounts for up to 4 days prior to the date of sample collection, a subset of water-quality samples taken under base-flow conditions was developed. To evaluate the TN and TP concentration data used in this report, water-quality data were partitioned into three categories—base flow (less than 0.2 inches of precipitation for up to 4 days prior to sampling), runoff (more than 0.75 inches of precipitation prior to and/or during sampling) and base flow plus runoff (all other conditions).

Figure 4. Map showing precipitation data-collection stations from which data were used to estimate base-flow nutrient loads.

Base-Flow Separation

Annual and seasonal volumetric base-flow values were required for calculating base-flow nutrient loads and yields. Daily mean discharge data for six continuous streamflow gaging stations (fig. 5, table 3) in the BB-LEH watershed were retrieved from the USGS' National Water Information System (NWIS). For the six streams, the data set was extrapolated to include the period of interest (1989-2011) by relating annual and seasonal precipitation to available discharge data. There are not sufficient numbers of sites or years of streamflow data to fully characterize the surface-water hydrology of the BB-LEH watershed (fig. 5, table 3). Therefore, the simplified water-budget relation (equation 5), combined with base-flow-separation techniques applied to the six streams with continuous streamflow data, was used to obtain base-flow volumes throughout the BB-LEH watershed.

Figure 5. Map showing streamflow gages in the Barnegat Bay-Little Egg Harbor watershed.

Table 3. Continuous streamflow-gaging stations and base-flow indices for six streams in the Barnegat Bay-Little Egg Harbor Watershed, N.J.

The base-flow separation program "BFI" (Wahl and Wahl, 1995) was used to determine the base-flow fraction of flow for each stream (the base-flow index, or BFI). The BFI is calculated as the ratio of base-flow volume (the area under the hydrograph curve remaining after all runoff peaks have been subtracted), divided by the total streamflow volume. The program detects the beginning and end of runoff events by changes in the slope of the hydrograph.

A second estimate of base flow was provided by the USGS program PART (Rutledge, 1998), which uses streamflow partitioning to estimate a daily record of base flow in a slightly different manner than the BFI program. PART scans the hydrograph for days that fit the requirements of antecedent recession, and designates those days as base flow. The base-flow fraction of flow that occurs during each runoff event is determined by linearly interpolating between flow at the beginning and end of the event, thus separating the runoff portion of flow from the base-flow portion. All base-flow portions are totaled, and the ratio of the total base-flow volume to the total streamflow volume represents the base-flow index. The PART program is applied to a long (multi-year) period of record to give an estimate of the mean rate of ground-water discharge.

Average BFI values for the six basins range from 0.647 to 0.897, indicating that base flow accounts for approximately 65 to 90 percent of total streamflow for streams in the BB-LEH watershed, and that base-flow contributions to substantially exceed runoff contributions (table 3). The Metedeconk River is the most urbanized of the six basins (39.8 percent urban above station 01408120 on the North Branch; 34.7 percent urban above station 01408150 on the South Branch), and has the smallest average

BFI values (0.669 and 0.647, for the north and south branches, respectively). Impervious surface from structures and pavement, soil compaction, and other urban characteristics increase flashiness and decrease recharge and base flow in streams (Aichele, 2005). The small base-flow volume is evident in the discharge hydrograph for North Branch Metedeconk (fig. 6A), which shows flow returning to low levels soon after runoff events when compared to recession patterns of the other streams (fig. 6 B-D). Runoff, which contributes more than 30 percent of flow volume in the Metedeconk River, is more significant in this stream than in streams in less-urbanized basins. If urban development in other basins was increased to the extent of the Metedeconk River basin, more runoff, less recharge to groundwater, and smaller proportions of base flow would be expected.

The Toms River basin above station 01408500 is the largest of the six basins (319 square kilometers) and is comprised of 22.4 percent urban land use. The discharge hydrograph for the Toms River for water year[1] 2010 (fig. 6 (B)) is similar to that of the Metedeconk River basin, as the same runoff events are represented; however, more gradual recession after runoff results in a higher base-flow index. In addition to the smaller percentage of urban land, the longer flow paths of this larger basin allow for more time and distance for recharge, leading to a higher BFI.

Discharge hydrographs for Cedar Creek and Westecunk Creek (fig. 6 C, D) are dominated by base flow (average BFI values of 0.786 and 0.845, respectively), reflecting their low levels of urban development. These two streams have gradual baseline recession, never approaching zero flow, even after extended dry periods.

From available discharge data, and results of base-flow separation, average inches of base flow (base-flow volume normalized by basin area) were calculated for each year and season. Annual base-flow values for the six gaged basins, and an average for the entire watershed (excluding Oyster Creek)

[1]A water year is the 12-month period beginning October 1 of any given year and extending through September 30 of the following year. The water year is designated by the calendar year in which it ends and which includes 9 of the 12 months. Thus, the year ending September 30, 2007, is called the 2007 water year.

follow similar patterns (fig. 7). North Branch Metedeconk base flow tends to be slightly less than those of other local streams, and base flow at Westecunk Creek tends to be slightly greater. The differences in base flow among the streams correspond to differences in land use (urban development), hence impervious surface, between these two basins. On an annual basis, a close relation between precipitation and base flow is observed for all streams. Base flow at Oyster Creek, as previously mentioned, is substantially higher than at other streams in the watershed because it receives base flow contributions from the Oswego River. Total base flow does not vary substantially among the other five streams, indicating that the average of their area-weighted base-flow values is a reasonable approximation of base-flow for the entire BB-LEH watershed. Area-weighted annual and seasonal values of base flow were calculated for the watershed and applied to each HUC-14 subbasin for the calculation of base-flow loads.

Figure 6. Discharge hydrographs for water year 2010 for (A) North Branch Metedeconk River, (B) Toms River, (C) Cedar Creek, and (D) Westecunk Creek.

Figure 7. Comparison of precipitation with annual base flow for six gaged basins in the Barnegat Bay-Little Egg Harbor watershed and for the watershed as a whole, 1989-2011.

Determination of Baseflow-Mean Concentrations of Total Nitrogen and Total Phosphorus in Streams

Relations between measured concentrations of TN and TP and percentages of land uses in basins upstream of sampling locations were used to obtain BMCs for each HUC-14. As described earlier, based on geographic location (north or south), drainage area above a water-quality sampling site, and daily average precipitation amounts for up to 4 days prior to the date of sample collection, a subset of water-quality samples taken under base-flow conditions was developed. Only sites with four or more base-flow samples collected within a land-use period were used in the calculation of TN and TP base-flow loads. Sites that met this criterion varied by constituent. Figure 8 shows the sampling sites for which four or more TN and TP values are available for one or more land-use periods. Several sites in the northern, central and southern watershed segments had been sampled during multiple land-use periods, and several streams were sampled in more than one reach. Therefore, the variability in TN and TP over time, among segments, and with varying land-use patterns along the streams was reflected in the water-quality data. These data were used to determine best-fit-fit multiple linear regression models relating concentration (TN or TP) to land use. The average concentration at each site during each land-use period was related to land use (percents of the principal land uses) by determining the best-fit multiple linear regression model. Combinations of eight potential explanatory variables (percent of forest, water, wetlands, barren, agricultural, residential urban, nonresidential urban, impervious urban) were explored in multiple linear regression models. The parameters evaluated when selecting the best-fit regression equations were:

1. Statistical significance of explanatory variables, as indicated by t- and p-values
2. Model correlation coefficient, r^2
3. Colinearity among variables, as indicated by variance inflation factors (VIFs)
4. Difference between estimated and measured concentrations

Not all explanatory variables for the selected TN model were statistically significant based on a 95% confidence level (p-value <0.05); however, for the overall model, the calculated and measured values were correlated with an r^2 of 0.65. All explanatory variables for the TP model were statistically significant based on a 95% confidence level (p-value <0.05), and $r^2 = 0.77$. Colinearity among explanatory variables in the selected models was minimal as indicated by low VIFs; all VIFs were less than 8 for the TN model and less than 3 for the TP model. Measured and estimated concentrations were compared graphically with a scatterplot; for both the TN and TP models, the r^2 between the measured and calculated values was greater than 0.6.

The combination of explanatory variables that gave the best-fit model for TN was agriculture, forest, and combined urban (impervious urban plus residential urban plus nonresidential urban) (table 4). Agriculture, combined urban, and wetlands were the explanatory variables that yielded the best-fit model for TP (table 4). Based on the regression results, the highest regression coefficients are for agricultural land, and the lowest are for forested land, for both TN and TP.

Figure 8. Water-quality sampling stations in the Barnegat Bay-Little Egg Harbor watershed with four or more total nitrogen or total phosphorus base-flow samples available for one or more land-use years, 1986, 1995, 2002, 2007.

Table 4. Multiple linear regression coefficients for relating land use to base-flow concentrations of total nitrogen and total phosphorus.

The best-fit regression equations were applied to the land-use percentages of each HUC-14 subbasin for each land-use year to obtain estimated BMCs for each subbasin, such that, for TN:

$$BMC_{HUC14} = 0.7369 + 0.0658*AgPct - 0.0055 * ForPct + 0.0048 * CombUrbPct \quad (6)$$

Where,

BMC_{HUC14} = base-flow mean concentration for the HUC-14 subbasin

AgPct = Percent agricultural land in the HUC-14 subbasin

ForPct = Percent forest in the HUC-14 subbasin

CombUrbPct = Percent combined urban in the HUC-14 subbasin

and for TP,

$$lnBMC_{HUC14} = -5.3217 + 0.1115*AgPct + 0.0196 * CombUrbPct + 0.0259 * WetPct \quad (7)$$

Where,

$lnBMC_{HUC14}$ = natural log of the base-flow mean concentration for the HUC-14 subbasin

AgPct = Percent agricultural land in the HUC-14 subbasin

CombUrbPct = Percent combined urban in the HUC-14 subbasin

WetPct = Percent wetlands in the HUC-14 subbasin

The TN relation (equation 6) indicates that agricultural land has the greatest influence on increasing TN concentrations, urban land is intermediate in influence, and forested land has the least amount of influence. The TP relation (equation 7) indicates that agricultural land has the greatest influence, followed by wetland, followed by urban land.

Because land-use percentages differ among land-use years, this calculation was done for each HUC-14-land-use year combination. Base-flow loads for each HUC-14 subbasin were then calculated as the product of the BMC for the subbasin and the average base flow for the watershed, with a unit conversion. Yields were calculated as the HUC-14 load divided by the HUC-14 area.

Runoff Nutrient Load Calculation

Runoff Load Calculation Using PLOAD

PLOAD version 3.0 (U.S. Environmental Protection Agency, 2001) was used to quantify nutrients in runoff. PLOAD is a GIS-based application in which land-use percentages, contaminant intensity, and percent of impervious surface associated with each land-use type are used as explanatory variables for estimating concentrations, loads, and yields of selected contaminants in runoff. PLOAD is used to quantify nutrient loads from runoff to lakes and streams. Although a powerful tool for estimating contaminant loads over long timeframes, not all variability in nutrient loading can be explained by the variables used by PLOAD. Additionally, PLOAD does not account for in-stream processes that may increase or attenuate concentrations and loads of contaminants during transport through a watershed. It is, however, a suitable tool for comparing loads of nutrients in a watershed among seasons and years.

The PLOAD application requires the following data inputs: GIS land-use data; GIS watershed delineations; percent imperviousness for each land-use type; annual or seasonal precipitation; and annual or seasonal event-mean concentrations (EMCs) for each land-use type. The two equations used by PLOAD to calculate loads with the USEPA "Simple Method" (U.S. Environmental Protection Agency, 2001)—a runoff coefficient equation and a loading equation—are given below.

Runoff coefficients are calculated as:

$$R_{VU} = 0.05 + (0.009 \times I_U) \tag{7}$$

Where,

R_{VU} = Runoff coefficient for land use type u, $\text{inches}_{\text{runoff}}/\text{inches}_{\text{rain}}$

I_U = Percent imperviousness

The pollutant loads are then calculated with the following equation:

$$L_P = \sum_U (P \times P_J \times R_{VU} \times EMC_U \times A_U \times 2.72 / 12) \tag{8}$$

Where,

L_P = Pollutant load, lbs

P = Precipitation, inches/year

P_J = Ratio of storms producing runoff (default = 0.9)

R_{VU} = Runoff Coefficient for land use type u, $\text{inches}_{\text{runoff}}/\text{inches}_{\text{rain}}$

EMC_U = Event Mean Concentration for land use type u, milligrams/liter

A_U = Area of land use type u, acres

Resulting load and yield values from PLOAD outputs were converted to metric units.

Percent Imperviousness

Percent imperviousness (I_U) is a function of land use, with more impervious surface being attributed to urban land than agricultural and forested land. Percent imperviousness values range from 0-95% for the eight land-use categories used in this investigation (table 5). Although the PLOAD documentation does not provide guidance for selecting I_U values, an example table of percent impervious values was provided in the PLOAD application. Published values are also available from literature sources (Washburn and others, 2010; Prisloe and others, 2003; City of Redmond, WA, 2009). Residential (I_U) for the BB-LEH watershed was set at 31%, which is consistent with the California (I_U) for the mean residential unit density of about 1.6 units per acre for the BB-LEH watershed, as calculated from data compiled by Lathrop and Conway (2001). This value also is consistent with the I_U of 30.5% determined for residential, single unit, medium-density land use in the Upper Delaware Watershed (North Jersey Resource Conservation & Development, 2002). Nonresidential urban land use was assigned an I_U value of 60%, reflecting a composition of retail, office, industrial, and public nonresidential land uses, which have I_U values of 50-86% (Washburn and others, 2010). I_U values for agricultural, forest, barren land, and wetland categories were given values of 2%, consistent with those of the open space and agriculture categories of Washburn and others (2010) which range from 2-4%. Impervious urban was given a value of 95% because urban impervious surfaces such as pavement and structures often do not provide perfect water barriers due to cracks and other imperfections. Open water was given a value of 0% impervious.

Table 5. Percent imperviousness values used to calculate runoff nutrient loads.

Monthly, Seasonal, and Annual Precipitation

Monthly precipitation data were retrieved from the Office of the New Jersey State Climatologist and from the National Climatic Data Center. These data were used to calculate growing season, nongrowing season, and annual precipitation totals for the entire watershed, which were subsequently used as input into PLOAD. PLOAD utilizes a single precipitation amount for the entire area (in this case, the BB-LEH watershed) for each year. Precipitation records from eight stations were used (fig. 9). Averages of precipitation totals from two southern stations (Atlantic City Airport and Atlantic City Marina), four western stations (Hammonton, Pemberton, Mount Holly and Indian Mills) and two northern stations (Toms River and Lakehurst) were averaged together to obtain an overall average precipitation total, by year and by season, for the BB-LEH watershed for 1989-2011. Precipitation records from most stations are incomplete (missing months or years of data); however, data from at least four stations were used to calculate each average annual and seasonal precipitation total.

Figure 9. Map showing precipitation data-collection stations from which data were used to estimate runoff nutrient loads.

Determination of Event-Mean Concentrations

Event-mean concentrations (EMCs) are flow-weighted concentrations of water-quality constituents under runoff or high-flow conditions, and are used in watershed-based calculations and models for calculating contaminant loads (Lin, 2004; Baird and others, 1996). The EMC for a given constituent can vary widely as a function of land use, geographic location, seasonality, and other variables. For this study, an EMC value was developed for each land-use type and season combination. The EMCs were input into PLOAD to calculate runoff loads and yields for each HUC-14 subbasin.

EMC values can be determined from local water-quality and stream-flow records, or can be assigned from literature values (for example, Syed and Jodoin, 2006). For this report, local water-quality and streamflow data were used to determine the EMC values for TN and TP. The process of determining land-use EMCs involved the following steps:

(1) select basins representative of the study area for which sufficient water-quality and hydrologic data are available,

(2) determine the land-use percentages of each basin above its sampling locations,

(3) compile water-quality data and hydrologic data for days in which storm runoff occurred,

(4) determine streamflow for each sample date and time ,

(5) calculate the flow-weighted mean concentration (EMC) for each constituent of interest at each site, and

(6) use a stepwise regression procedure to calculate the EMC for each land-use category

For TN and TP, seasonal and annual EMCs were estimated for each land-use category: agricultural, barren land, forest, impervious urban, residential urban, nonresidential urban, wetland, and water. Water-quality and streamflow data from two studies with a large number of storm-flow samples were used to develop the EMCs. Only water-quality data from runoff samples were used to determine EMCs. In one study, locations on Long Swamp Creek, Davenport Branch, and Wrangle Brook, all in the BB-LEH watershed and all tributaries to the Toms River, were sampled for nutrients multiple times during 15-19 storms from 1994 to 1999 (Baker and Hunchak-Kariouk, 2007) (table 6). Data from that study provided extensive storm-flow water-quality and hydrologic data. In another study, five sites located on tributaries to the Lower Delaware River (also located in the New Jersey Coastal Plain) were sampled in an intensive investigation of water quality and hydrology from 2002 to 2007 (Baker and

Esralew, 2010) (table 6). These data were used to supplement data from the BB-LEH watershed sites for computation of EMCs. The water-quality data from these two studies were collected by the New Jersey Department of Environmental Protection, and are archived in the USEPA's STORET database. The hydrologic data are archived in the USGS's NWIS database.

Table 6. Stations from which water-quality data collected during runoff conditions were used to calculate EMCs.

The GIS land-use datasets that corresponded most closely to the years of water-quality sampling were used to determine land-use percentages for each basin: 1995 land use for the Toms River watershed sites, and 2002 land use for the Lower Delaware River watershed sites. Basins were delineated using the USGS application StreamStats (Ries and others, 2004), and basin land-use percentages were obtained from GIS coverages, except for two stations (01482890 and 0146452750) for which land-use percentages were obtained from Baker and Esralew (2010) (table 7).

Table 7. Land-use distributions for nine water-quality sampling sites used in the development of EMCs.

Flow-weighted mean concentrations were calculated as the total mass of a constituent divided by the total flow volume during the sampled portion of a runoff event. To accomplish this computation, masses for the periods between samples were calculated as the sample concentration multiplied by the flow volume between samples. The sum of these incremental masses is the total mass, and the sum of the incremental flow volumes is the total flow volume. The ratio of total mass divided by total flow volume, with a unit adjustment, gives the flow-weighted mean concentration (EMC) for that sampling location. This procedure was completed for annual and seasonal conditions for TN and TP.

Because EMC values were required for land-use categories, a relation between EMCs and land use for the ten stations listed in table 6 was required. The sum of area-weighted land-use EMC (EMC_{LU}) values in a basin is equal to the EMC for the basin (EMC_{basin}):

$$EMC_{basin} = (A_{LU1} \text{ x } EMC_{LU1} + A_{LU2} \text{ x } EMC_{LU2} + A_{LU3} \text{ x } EMC_{LU3} + A_{LU4} \text{ x } EMC_{LU4} + \ldots)/A_T \quad (9)$$

where

A_{LU1}, $A_{LU\,2}$ … are areas of land-use 1, land-use 2…

EMC_{LU1}, EMC_{LU2}… are the event-mean concentrations for land-use 1, land-use 2…

A_T is the total basin area.

Basins with little agricultural land were used to determine EMC_{LU} values for forest, wetland, and residential and nonresidential urban categories. For TN, six basins, each comprised of more than 94 percent of these land-use categories were used to calculate the EMC_{LU} values, and for TP, five basins, each comprised of more than 92 percent of these land-use categories were used to calculate EMC_{LU} values. For both TN and TP, EMC_{LU} values were initially assigned default values suggested by the PLOAD application and the EMC_{basin} values were then calculated for each of the basins. A stepwise procedure was developed to adjust the default EMC_{LU} values so that they were more reflective of measured concentrations in the study area; EMC_{LU} values were raised or lowered incrementally such that the difference between EMC_{basin} values calculated from equation 9 (referred to as the “calculated EMC_{basin}”) and those determined from water-quality and hydrologic data (referred to as the “measured EMC_{basin}”) was minimized, and the correlation coefficient between the calculated and measured EMC_{basin} values was maximized. Tables 8 and 9 and figure 10 (A) and (B) show the results of applying this procedure for determining the final EMC_{LU} values for TN and TP. Barren land was given the same EMC_{LU} value as forested land, as both categories are undeveloped and not affected by urban or agricultural activities. EMC_{LU} values used as input into PLOAD are shown in table 10 for year-round, growing and non-growing seasons.

Table 8. Comparison of calculated and measured total nitrogen event-mean concentration values for six water-quality sampling sites.

Table 9. Comparison of calculated and measured total phosphorus event-mean concentration values for five water-quality sampling sites.

Figure 10. Comparison of calculated and measured event-mean concentration (EMC) values for (*A*) total nitrogen and (*B*) total phosphorus.

Table 10. Event-mean concentrations used to calculate runoff nutrient loads for each land-use category for year-round, growing, and nongrowing seasons.

Although the total percent of agricultural land use in the BB-LEH watershed has been minor during this investigation, some HUC-14 areas have sufficient agricultural land to possibly affect surface-water quality. Insufficient nutrient-concentration data are available for sites in the BB-LEH watershed with large concentrations of agricultural land use for determining EMC values for agricultural land. Therefore, two sites in the Lower Delaware River watershed were used to calculate agricultural EMCs. As of 2002, sites 0146452750 (Blacks Creek near Chesterfield) and 01482890 (Alloway Creek near Watsons Corner NJ) had 55.4 and 76.6 percent agricultural land use, respectively (Baker and Esralew, 2010). Agriculture in the Blacks Creek basin is mostly row crops. Cattle production is practiced in the Alloway basin, and cattle were frequently observed in and around

Alloway Creek during water-quality sampling events (Baker and Esralew, 2010). Using water-quality data from both of these streams in the determination of the agricultural EMCs assures that the effects of a variety of agricultural activities are considered. The relation shown in equation 9 was modified to calculate agricultural EMC_{LU} values, with a term added for agricultural land use and the urban categories combined.

As a means of evaluating the reasonableness of the EMCs used in the runoff calculations, mean runoff concentrations were calculated for each of the basins upstream of water-quality sampling stations with four or more samples during one or more land-use periods, as the sum of the same EMC_{LU} values input into the PLOAD calculation (table 10), multiplied by the percent of the respective land uses in each sample basin. For TN, the average percent difference between the measured mean concentration and the calculated mean concentration was 27.4 percent. The average mean TN concentration at the watershed scale (24 site/land-use year combinations) was 0.64 mg/L for measured values and 0.66 mg/L for calculated values. The average mean TN concentration for sites in the north segment was 0.84 and 0.82 mg/L for measured and calculated values, respectively. For the central segment, the average mean TN concentration was 0.35 and 0.46 mg/L for measured and calculated values, respectively, and for the south segment, it was 0.43 and 0.47 mg/L, respectively. This agreement between the measured and calculated values suggests that the EMCs developed for TN are reasonable on a watershed scale as well as at the segment level, although there may be some overestimation in the less-developed central segment.

As with TN, mean runoff TP concentrations for streams in which four or more samples had been collected during a land-use period (20 site/land-use year combinations) were compared to TP concentrations calculated from EMCs. Although the relation between the measured and calculated TP concentrations was good ($r^2 = 0.79$), the EMCs systematically overestimated the concentrations, resulting in an average ratio of 0.57:1 for measured:calculated values. This reflects the fact that, though similar, the current and historical land-use patterns of the Lower Delaware River watershed streams are different from those in the BB-LEH watershed. For example, more land was and continues to be used for agriculture in the Lower Delaware River watershed. To account for the overestimation and to more accurately reflect the actual water-quality conditions in the BB-LEH watershed, TP concentrations calculated from the EMCs were adjusted by applying a calibration factor of 0.57 (average ratio of measured to calculated concentrations). After calibration, the average mean TP concentration at the watershed scale was 0.038 mg/L for measured values and 0.036 mg/L for calculated values. The average mean TP concentration for sites in the north segment was 0.043 and 0.040 mg/L for measured and calculated values, respectively. For the central segment, it was 0.005 and 0.007 mg/L for measured and calculated values, respectively, and for the south segment, it was 0.009 and 0.014 mg/L, respectively. The agreement between measured and calibrated values at the watershed and segment scale indicates that the EMCs developed for TP are reasonable when a correction factor is applied; however, there may be some overestimation in the less-developed segments.

Calibration

The equations used in PLOAD to calculate loads from EMCs, precipitation, and relations between land use and permeability. These relations may not represent conditions present in a particular watershed being simulated if permeabilities, hence runoff volumes, are different from those associated with the various land uses. In the case of the BB-LEH watershed, hydrologic records and base-flow separation indicate that only about 15-35 percent of flow in most streams is from runoff. To calibrate the PLOAD loads and yields to actual runoff in the watershed, runoff (in inches) was calculated from PLOAD results and compared to that determined from the hydrologic record and base-flow separation.

The average annual runoff for the BB-LEH watershed from the hydrologic record (1989-2011) determined from base-flow separation was 5.78 inches, whereas the average annual runoff estimated from PLOAD results was 8.27 inches. This overestimation may be attributed to the extremely flat topography of the BB-LEH watershed (and the entire New Jersey Coastal Plain), and the highly permeable, sandy soils that underlie the watershed, both of which enhance recharge (Watt, 2000). PLOAD is designed to apply to typical conditions, where the base-flow index would tend to be lower, and runoff values would be higher. Therefore, all load and yield values determined by PLOAD were multiplied by a factor of 0.70 (ratio of runoff calculated from the hydrologic record to that derived from PLOAD results) to account for PLOAD's overestimation of flow and to more accurately reflect the hydrologic conditions of the watershed. By applying this correction factor, the accuracy of TN and TP loading in runoff from available water-quality, precipitation, and hydrologic data has been optimized within the limitations of the PLOAD application.

Turf Analysis

A substantial portion of the watershed consists of single-family dwellings or other types of land uses with extensive areas in lawns, also referred to as turf. Prior work in Barnegat Bay and in Buzzards Bay, Massachusetts indicates that managed turf or lawn areas can represent substantial sources of nitrogen runoff to estuarine waters (Bowen and others, 2007; Buzzards Bay National Estuary Program, 2012).

Remote-sensing data and geographic information systems (GIS) were used to map and quantify turf areas across the Barnegat Bay watershed. The New Jersey Department of Environmental Protection (NJDEP) spring 2007 color infrared aerial photography was used as the basis for the image analysis. The 2007 NJ Land Use/Land Cover data set was used to extract out urban land use areas for further analysis (fig. 11). The objective was to delineate what areas in urban land uses were dominated by turf/lawn land cover.

Figure 11. Map showing developed areas within the Barnegat Bay-Little Egg Harbor watershed based on 2007 land use, and boundaries of the aerial photographic image tiles, based on 2007 aerial photography.

The eCognition software package (Definiens Developer 7) was used to segment the aerial photographic imagery into relatively small homogeneous image objects (i.e., groups of image pixels with similar spectral color and pattern that were on the order of 0.25 to 0.5 acre in size). These image objects were then displayed as GIS polygons overlain on the original aerial photographic imagery (fig. 12).

Figure 12. Example of the image object polygons and the randomly selected points and the visually interpreted classification into turf and non-turf categories.

A subset of the larger study area was used to develop a training dataset of over 1,000 randomly selected GIS polygons. The selected GIS polygons were classified by on-screen visual interpretation of the 2007 aerial photography into either 1) turf; 2) managed turf or 3) non-turf categories (fig. 12). The turf category represents land cover areas dominated by grasses/herbs that are mowed on at least an annual basis. The managed turf category represents grassed or lawn areas that receive a higher intensity of management, including both fertilization and irrigation.

This training dataset, along with a random forest version of the Cartographic and Regression Tree (CART) analysis, was used to classify the image object polygons. Random forest uses a bootstrap version of the CART model without replacement. Bootstrapping involves randomly sub-sampling the training dataset, running a CART model and then using the remaining training dataset to compute an accuracy assessment. The random forest model was developed within a MATLAB script. This technique provides an un-biased accuracy assessment while allowing the full training dataset to be used in the final model creation. A reference manual for this statistical technique is located at *http://cran.r-project.org/web/packages/randomForest/randomForest.pdf*.

The classified image object polygons were then overlain on the imagery and then further quality checked and the turf classification modified as necessary (fig. 13). An additional accuracy assessment of the turf areas was created by randomly selecting 450 image object polygons dispersed across the study area and manually classifying them as turf or non-turf. This independent classification was then compared to the prior classification (as described above) for these selected polygons as a means to assess the accuracy of the turf mapping effort.

Figure 13. Example of the mapped output of the Random Forest model and after further in-screen quality checking and updating.

Although the original intention of this classification work was to distinguish intensively managed from less intensively managed turf, a visual assessment of the Random Forest classification results indicated that such classification was not feasible, so intensively and less intensively managed turf were grouped into one category. The accuracy assessment indicated that turf could be mapped with an approximately 90% accuracy and a kappa statistic of 0.75 (table 11). The turf mapping was deemed of sufficiently high accuracy (approximately 90%) to be used to investigate relations between turf area and nutrient loads in the watershed. A visual assessment indicated that the turf coverage was highest in newer, large-lot residential areas with minimal tree cover. There may be some underestimation of turf growing under a canopy of shade trees, especially in older residential neighborhoods.

Table 11. Accuracy assessment of turf mapping.

Evaluation of Available Water-Quality Data

The following section summarizes the compiled TN and TP concentration data, and compares differences in concentrations among the watershed segments. The data used in this analysis are pooled, containing concentration values from base-flow and runoff samples collected during all seasons. Although water-quality samples were collected over an extended period of time and sampling locations are not distributed uniformly throughout each segment, comparing summary statistics of nutrient concentrations among the segments is informative.

Total nitrogen data available for years 1980-2011 consisted of 1,100 quality-assured values from 50 sites throughout the watershed. The north segment was most frequently sampled (848 values from 34 sites), followed by the central segment (171 values from 9 sites) and the south segment (81 values from 7 sites). Median TN concentrations were 0.79, 0.23, and 0.31 mg/L as N for the north, central, and south segments, respectively (table 12). The order of median TN concentration among watershed segments is consistent with the order of percent developed land. The ANOVA by ranks test, followed by a Tukey multiple comparison test, were used to test the null hypothesis of no difference among segments and to rank the segments by median TN concentration. The null hypothesis was rejected at the 5% significance level ($P < 0.05$), and the order of median TN concentrations among segments based on available water-quality data is:

$$TN_{north} > TN_{south} > TN_{central}$$

The median TN concentration in the highly-developed northern segment is significantly higher than that of the south segment, which is significantly higher than that of the central segment (fig. 14).

Table 12. Summary statistics for total nitrogen (1980-2011) and total phosphorus data (1991-2011) compiled for the Barnegat Bay-Little Egg Harbor watershed.

Figure 14. Boxplot of surface-water concentrations of total nitrogen in the Barnegat Bay-Little Egg Harbor watershed by watershed segment, 1980-2011.

A total of 817 TP values for years 1991-2011 were available for 82 sites in the BB-LEH watershed. Of those sites, 63 sites are located in the north segment (667 values), 11 in the central segment (117 values) and 8 in the south segment (33 values). Total phosphorus data also were evaluated for differences among segments. Median TP concentrations were 0.030, <0.010, and <0.015 mg/L as P in the north, central, and south segments, respectively (table 12). For the ANOVA by ranks test, the null hypothesis of no difference among segments was rejected at the 5% significance level ($P < 0.05$). The Tukey multiple comparison test ranked median TP concentrations by segment such that:

$TP_{north} > (TP_{south} = TP_{central})$

The median TP concentration in the highly-developed north segment is significantly higher than that of the two less-developed segments, which cannot be statistically distinguished from each other (fig. 15).

Higher median concentrations of both TN and TP in the north segment are consistent with a greater percent of developed land (agricultural plus urban) in the north segment (fig. 16). These relations demonstrate well-established effects of development on water quality. Based on previous investigations in the watershed (Hunchak-Kariouk and Nicholson, 2001; Baker and Hunchak-Kariouk, 2006; Wieben and Baker, 2009), and the analysis of existing data, future increases in development in the central and south segments will likely lead to higher concentrations and loads of nutrients in the streams located in those areas. Given that concentrations are a primary factor influencing loads, the higher concentration (as a function of land use) in the north are reflected in the loads, as will be described later.

Figure 15. Boxplot of surface-water concentrations of total phosphorus in the Barnegat Bay-Little Egg Harbor watershed by watershed segment, 1991-2011.

Figure 16. Relations between median of average concentrations of total nitrogen (TN, 1980-2011) and total phosphorus (TP, 1991-2011), and percent developed land (urban plus agricultural, average of 1986, 1995, 2002, and 2007 for TN, and 1995, 2002, and 2007 for TP).

An assumption was made that a single EMC value would be used by PLOAD for each land-use category during each season, regardless of sampling location or streamflow. Previous water-quality investigations of the BB-LEH watershed have shown that concentrations of nutrient species can vary substantially over the course of a storm event (Baker and Hunchak-Kariouk, 2006; Wieben and others, 2013). Runoff data used to calculate the EMCs were collected during various storms and at various times during storms (rising, peak, and falling limbs of the hydrograph) and therefore the calculations take into account variability in runoff concentrations.

As described earlier, relations between land-use categories and TN and TP concentrations are significant and consistent for both base flow and runoff. Therefore, use of these relations to calculate loading for annual and seasonal time steps as used here is consistent with available water-quality data and previous studies. Annual and seasonal variability of TN and TP loading from the BB-LEH watershed is predictable from land-use percentages and the precipitation record. This relation is true for the watershed as a whole, as well as for the three segments.

Estimates of Total Nutrient Loads

Concentration, load, and yield data were determined at the HUC-14 scale for base-flow and runoff conditions (table 13). Loads also were calculated at the watershed segment scale (table 14), and for the entire watershed (table 15). The factors that control loading at various scales (watershed, segment, or HUC-14) are land use (and related contaminant concentrations) and drainage area (and related streamflow volume). These factors dictate that the north segment should have the highest loads. During the period of study 1989-2011, total surface-water loads of TN (baseflow plus runoff loads) for the entire BB-LEH watershed ranged from about 522,000 kg as N (1995) to more than 921,000 kg as N (2011) (table 15). The north segment accounted for an average of 65.9 percent of the annual TN load, and the central and south segments accounted for 17.6 and 16.6 percent, respectively. Total phosphorus

(TP) loads for the watershed ranged from 22,800 (1995) to 40,200 kg as P (2011). Similar to TN, about 64.9 percent of the TP load was contributed by the north segment, 17.6 percent by the central, and 17.5 percent by the south segments. The large percentage of loads discharging from the north segment is attributed to a combination of factors: the north segment is more than twice the size of the central or south segments, contains the Toms and Metedeconk Rivers which together make up more than 60 percent of the streamflow in the watershed, and contains greater proportions of agricultural, and residential and non-residential urban lands, each of which are associated with greater mean nutrient concentrations than undeveloped land. The corresponding north segment of the estuary is the smallest of the three estuarine segments (fig. 2). Differences between the size of the watershed and estuarine segments in the north may be a factor contributing to higher nitrogen concentrations in the northern part of the estuary, as previously reported in Seitzinger and others (2001) and Kennish and Fertig (2012). Loads are similar for the central and south segments of the watershed, even though there is a greater proportion of urban development in the south segment, because of the larger drainage area of the central segment.

Table 13. Annual and seasonal base-flow, runoff, and total nutrient concentrations, loads, and yields for total nitrogen and total phosphorus for each HUC14 subbasin in the Barnegat Bay-Little Egg Harbor watershed, 1989-2011.

Table 14. Annual and seasonal base-flow, runoff, and total nutrient loads by watershed segment for total nitrogen and total phosphorus, 1989-2011.

Table 15. Annual and seasonal base-flow, runoff, and total nutrient loads for the Barnegat Bay-Little Egg Harbor watershed for total nitrogen and total phosphorus, 1989-2011.

Between 1989 and 2011, total loads fluctuated depending on precipitation and hydrologic conditions and patterns, with precipitation having a short-term and immediate effect on runoff loads and a longer-term effect on base-flow loads. For the entire period—on average—78.1 percent of the total TN load was carried in base flow, and 21.9 percent was carried in runoff. A smaller portion of TP was carried in base flow (67.1 percent on average) and 33.0 percent in runoff. The larger base-flow load for both constituents is consistent with the hydrologic record and the baseflow separation results obtained from both the BFI and PART programs. Additionally, the greater portion of TP carried in runoff as compared to TN is consistent with the fact that phosphorus adsorbs to sediments and is often resuspended from scouring of streambed sediments during runoff events.

Base-Flow Loads on the Watershed Scale

Using baseflow separation to determine annual and seasonal base-flow amounts, and relationships between base-flow mean concentrations and land use, nutrient base-flow loads were estimated by year and season for each HUC-14 subbasin in the BB-LEH watershed for the years 1989-2011. Annual TN base-flow loads for the watershed ranged from 405,000 kg as N (1995) to 714,000 kg as N (2011), and annual TP base-flow loads ranged from 15,200 kg as P (1995) to 26,700 kg as P (2011) (table 15, fig. 17). For both TN and TP, the lowest base-flow load occurred in 1995, corresponding to the driest year. The highest base-flow load for TN and TP was in 2011. 2011 was the second-wettest year in the period of study (57.32 in.) and followed a comparatively dry year (2010, 43.23 in.). 2009 was the wettest year with 59.92 in. The increase in baseflow loads between 2009 and 2011 despite a substantial dip in precipitation is likely the result of high amounts of recharge from 2009 continuing to seep through the surficial aquifer to the streams, in combination with additional recharge from 2011. Years with the highest flow do not necessarily correspond to years with the highest precipitation. (fig 17).

Figure 17. Base-flow loads by year and season for (A) total nitrogen and (B) total phosphorus for the Barnegat Bay-Little Egg Harbor watershed, 1989-2011.

Figure 17 shows that there appears to be a gradual increase in base-flow loads for 1989-2011; however, that increase is masked by a large amount of inter-year variability resulting from precipitation patterns. There is a strong relationship between precipitation patterns over a series of years, and subsequent effects on streamflow volume and base-flow load. However, loads are a function of both hydrologic condition and land use. Increases in the amount of urban development in the watershed over time, in conjunction with the strong relation between urban land and higher nutrient concentrations indicate that the gradual increase in base-flow loads shown in figure 17 can be attributed in part to increases in development in the watershed.

For both TN and TP, the relative contribution of base-flow loads during the growing and non-growing seasons is similar, with the growing season accounting for an average of 53.8 percent, and the non-growing season accounting for an average of 46.2 percent, of the annual base-flow loads (table 15). One may expect loads to be lower during the non-growing season because of the shorter length of the non-growing season. However, a higher percent of precipitation is recharged during the non-growing season because of lower rates of evapotranspiration and less agricultural and urban water use. This seasonal recharge, in turn, results in proportionally higher base flows during the non-growing season.

Base-Flow Loads on a Segment Scale

For TN, annual base-flow loads for the north segment ranged from approximately 266,000 to 461,000 kg as N, comprising an average of 65.1 percent of the annual TN base-flow load for the watershed (table 14). The central segment contributed 73,100-130,000 kg as N and the south segment contributed 66,600-123,000 kg as N, accounting for an average of 18.1 and 16.8 percent of the annual TN base-flow load, respectively (table 14). For TP, annual base-flow loads for the north segment ranged from 9,330 to 16,300 kg as P, comprising an average of 61.4 percent of the base-flow TP load for the watershed. The central segment contributed 2,970-5,210 kg as P and the south segment contributed 2,880-5,140 kg as P accounting for an average of 19.4 and 19.1 percent of the annual TP base-flow load for the watershed, respectively. Loads contributed by the north segment are substantially higher than the other two segments in part because the drainage area is considerably larger for the north segment, there is a substantially greater volume of streamflow in the north, and also because of the greater amount of urban and agricultural development in the north. The central segment contributes a similar or slightly higher proportion of nutrients from base flow as compared to the south segment despite less development because of a larger drainage area for the central segment.

Base-Flow Loads on a HUC-14 Scale

Figure 18 shows maps of annual base-flow TN and TP loads for each HUC-14 subbasin in the BB-LEH watershed for 1995 and 2011 to demonstrate differences in the distribution of base-flow loads during the most extreme hydrologic conditions that occurred in the watershed between 1989 and 2011. Darker-colored areas represent subbasins having greater base-flow loads than lighter-colored areas. 1995 represents the year with the lowest amount of base flow as a result of low-flow conditions. 2011, on the other hand, was a very wet year during which streamflow volume was the greatest.

Figure 18. Map showing annual base-flow loads for each HUC14 subbasin in the Barnegat Bay-Little Egg Harbor watershed for total nitrogen for (A) 1995 and (B) 2011, and for total phosphorus for (C) 1995 and (D) 2011.

Comparison of the low-flow and high-flow years shows the effects of streamflow volume on the distribution of base-flow loads, in that there are a greater number of HUC-14s with higher nutrient loads during the high-flow years. For example, in 2011 there were twenty HUC-14s that contributed more than 12,000 kg as N to the total base-flow load, whereas in 1995, 3 HUC-14s contributed more 12,000 kg as N. Similarly, in 2011, there were nineteen HUC-14s with greater than 450 kg as P in base flow; in 2002, six HUC-14s contributed more than 400 kg as P in base flow. Although there is a larger number of subbasins in the north segment that contribute the greatest loads (during either dry or wet years), subbasins that contribute high base-flow loads are also found in the central and south segments, particularly along the coast. This range of base-flow nutrient loads among HUC-14 subbasins in the watershed is a result of the fact that two variables are at play in calculating loads—drainage area and contribution per unit area (related to land use).

Base-Flow Yields on a HUC-14 Scale

Loads are a measure of the total contribution of nutrients from a given area, whereas yields (loads normalized by area) are a measure of the intensity of the contribution. In terms of nutrients, yields are typically a reflection of land use. A complete list of all yields estimated for each HUC-14 subbasin for 1989-2011 is found in table 13. The distribution of the HUC-14 subbasins with the highest yields of TN or TP for 2011 (fig. 19) differs from that of the highest loads for the same year (fig. 18 (B) and (D)). For 2011, TN yields in base flow at the HUC-14 scale ranged from 1.66 to 8.96 kg/ha/yr (table 13). Total phosphorus yields ranged from 0.05 to 0.47 kg/ha/yr. Subbasins with the highest yields in base flow are primarily concentrated in the northern part of the watershed, and have higher proportions of agriculture and urban land. Subbasins with the lowest yields are dominated by forest cover.

Figure 19. Map showing yields of (A) total nitrogen and (B) total phosphorus in base flow for each HUC14 subbasin in the Barnegat Bay-Little Egg Harbor watershed for 2011.

Estimates of Runoff Nutrient Loads and Yields

Runoff Loads on the Watershed Scale

Using PLOAD, nutrient runoff loads were estimated by year and season for each HUC-14 subbasin in the BB-LEH watershed for the years 1989-2011. Between 1989 and 2011, runoff loads for TN ranged from approximately 117,000 to 216,000 kg as N, with the two greatest amounts occurring during very wet, recent land-use years (2009 and 2011; table 15). On average, the growing season accounts for 65.2 percent, and the non-growing season accounts for 34.8 percent, of the annual TN runoff load. Runoff loads for total phosphorus ranged from approximately 7,670 to 14,200 kg as P. Total phosphorus loads in runoff follow a similar pattern to TN, with loads increasing with precipitation and changes in land use. On average, the growing season accounts for 74.8 percent, and the non-growing season accounts for 25.2 percent, of the annual TP runoff load. The greater contribution of both TN and TP in runoff during the growing season is a result of the use of higher EMCs during the growing season and the fact that the growing season is two months longer than the non-growing season, which in turn affects precipitation amounts and runoff volume.

Runoff Loads on a Segment Scale

For TN, annual runoff loads for the north segment ranged from approximately 80,300 to 148,000 kg as N, comprising an average of 68.6 percent of the annual runoff load for the watershed (table 14). Annual TN runoff loads for the central and south segments had similar ranges (18,000-35,000 kg as N), each comprising an average of 15.7 percent of the annual TN runoff load (table 14). For TP, annual runoff loads for the north segment ranged from 5,560 to 10,100 kg as P, accounting for an average of 72.1 percent of the annual runoff load for the watershed (table 14). The central and south segments contributed between 1,040 and 2,090 kg as P annually, accounting for an average of 13.7 and 14.1 percent of the annual TP runoff load, respectively (table 14). Loads contributed by the north segment are substantially higher than the other two segments in part because the drainage area of the north segment is considerably larger, and because of the greater amount of urban development in the north. The central and south segments contribute a similar proportion of nutrients in runoff despite the larger size of the central segment, as a result of more extensive urban development in the south segment.

Runoff Loads on a HUC-14 Scale

In general, there is a greater frequency of HUC-14s with higher runoff load amounts in the northern portion of the watershed and along the eastern edge of the mainland part of the watershed (fig. 20). In terms of annual conditions, 1989 and 1990 (fig. 20 (A) and (B)) correspond to an early land-use year (1986) under relatively wet (annual precipitation = 53.83 in.) and dry (43.18 in.) conditions, respectively. 2009 and 2010 (fig. 20 (C) and (D)) correspond to the most recent land-use year (2007) under relatively wet (59.92 in.) and dry (43.23 in.) conditions), respectively.

Figure 20. Map showing annual runoff loads for total nitrogen for each HUC14 subbasin in the Barnegat Bay-Little Egg Harbor watershed for (*A*) 1989, (*B*) 1990, (*C*) 2009, and (*D*) 2010.

Comparison of the wet and dry years that occurred during the 1986 and 2007 land-use periods shows the effects of precipitation on the distribution of runoff loads, in that there are a greater number of HUC-14s with higher TN loads during the wet years (1989 and 2009). For example, in 2009 there were six HUC-14s that contributed more than 6,000 kg as N in their runoff load, whereas in 2010, a year marked by substantially less precipitation but in the same land-use period, no HUC-14s contributed more than 6,000 kg as N (fig. 20).

Comparison of the different land-use years with similar precipitation totals demonstrates the effects of land use on the distribution of runoff loads, in that there are a greater number of HUC-14s with higher TN loads during the more recent land-use periods. For example, in 2010 (based on 2007 land use), there were nine HUC-14s that contributed more than 4,000 kg as N in their runoff load, whereas in 1990 (based on 1986 land use), three HUC-14s contributed more than 4,000 kg as N.

Maps of seasonal runoff loads of TP at the HUC-14 scale in 1994 (fig. 21 A and B) show that greater event-mean concentrations (table 10) and more days in the season result in substantially larger loads in the growing season. Although a similar amount of precipitation fell on the watershed during the 1994 growing and non-growing seasons, the total phosphorus runoff load exceeded 100 kg as P in nineteen HUC-14s during the growing season, but in only four HUC-14s during the non-growing season.

Figure 21. Map showing seasonal runoff loads for total phosphorus for each HUC14 subbasin in the BB-LEH watershed for (*A*) 1994 growing, (*B*) 1994 nongrowing, (*C*) 2009 growing, and (*D*) 2008 nongrowing seasons.

Total precipitation for the watershed during the 2009 growing season was 39.95 in., the greatest of any seasonal precipitation amount for 1989-2011. The combination of more urban land than in previous years, growing-season EMCs, and extreme wet conditions resulted in the total phosphorus load exceeding more than 100 kg as P in 47 HUC-14s (more than half of the HUC-14s in the watershed), and of that, 14 subbasins contributed more than 250 kg as P in runoff (fig. 21C)

Similar to the effects of land use shown earlier for annual TN runoff loads, a comparison of figure 21 (B) and (D) shows the effects of land use on seasonal loads. Approximately 23.8 in. of precipitation fell on the watershed during both the 1994 and 2008 non-growing seasons. For the 2008 non-growing season (2007 land use) the runoff load exceeded 50 kg as P in twenty-three HUC-14s, with three greater than 100 kg as P. For the 1994 non-growing season (1995 land use), the runoff load exceeded 50 kg as P in 12 HUC-14s, with two greater than 100 kg as P. The greater frequency of higher runoff loads during the 2007 non-growing season is a result of increasing amounts of urban land in the watershed, which is associated with higher EMCs than other land uses (except for agriculture, which is declining as a land use in the watershed).

Runoff Yields on a HUC-14 Scale

TN and TP yields in runoff were generally greater in the northern, highly urban HUC-14 subbasins than in the more forested southern areas of the BB-LEH watershed in 2011 (fig. 22). Total nitrogen runoff yields at the HUC-14 scale ranged from 0.22 to 3.23 kg/ha/yr in 2011 (table 13). Total phosphorus yields in runoff ranged from 0.01 to 0.24 kg/ha/yr. Note that the ranges of yields of TN and TP in runoff are considerably lower than those for base flow (fig. 19). Subbasins with the highest yields in runoff are located primarily in the northeastern corner of the watershed, and are dominated by urban land uses. Subbasins with the lowest yields are predominantly forested (tables 1, 13).

Figure 22. Map showing yields of (A) total nitrogen and (B) total phosphorus in runoff for each HUC14 subbasin in the Barnegat Bay-Little Egg Harbor watershed for 2011.

Relations Between Turf Coverage, Land Use, and Nutrient Loads

The importance of turf (lawn) cover in contributing TN and TP to the BB-LEH estuary was investigated by redefining land use in the watershed as being in one of three categories: undeveloped, developed- turf, and developed- non-turf. These categories were established during the turf analysis process that was conducted for 2007. Regression models relating percentages of developed-turf and developed-non-turf land to concentrations of TN and TP were then used to explore relative contributions of nutrients from these land-use categories.

About 67.8% of the watershed area was deemed, by satellite imagery analysis for 2007, to be undeveloped and contain essentially no turf. Of the remaining area, 8.0% was classified as developed-turf, and 24.2% as developed- non-turf. Therefore, nearly one quarter (24.9%) of the developed land was mapped as turf (fig. 23). There is a strong relationship between percent turf and percent developed land (fig. 24) in the watershed, such that percent developed- turf typically increases with percent development, and the percent or area of total developed land can be considered a reasonable predictor of the percent or area of developed- turf land in the watershed. This relation does not hold true for eleven subbasins which are characterized by a high percentage of developed land but a very low percentage of turf (table 16), all located along the coast and the barrier islands. This dichotomy is the result of the close proximity of these subbasins to coastal areas, where residential landscaping often does not include lawns. Additionally, one inland subbasin (02040301070080) in the vicinity of the Lakehurst Naval Air Warfare Center is marked by a high percentage of developed land, of which a disproportionately high percentage is turf; this is likely because much of the area near landing strips located in the subbasin and a nearby golf course is turf. These twelve subbasins (table 16, fig. 24) are considered to be outliers (atypical of turf-coverage patterns in the rest of the watershed) and were excluded from the remainder of the turf analysis.

Table 16. Turf distribution within the Barnegat Bay-Little Egg Harbor watershed, based on 2007 land use.

Figure 23. Percent of turf and non-turf land cover in developed areas of the Barnegat Bay-Little Egg Harbor watershed, 2007 land use.

Figure 24. Graph showing the relation between percent turf and percent developed land in each HUC14 subbasin of the Barnegat Bay-Little Egg Harbor watershed, based on 2007 land use.

A strong relation between percent turf and annual yields of TN and TP in the BB-LEH watershed was observed for 2007 (fig. 25). There is a stronger relation between runoff yields and percent turf than between baseflow yields and percent turf. This difference is greater for TP than for

TN. These figures illustrate that storm runoff from urban turf is strongly related to yields, and therefore loads, of nutrients delivered to the estuary.

Figure 25. Graphs showing the relation between percent turf and total nitrogen yields in (A) total flow, (B) base flow, and (C) runoff, and between percent turf and total phosphorus yields in (D) total flow, (E) base flow, and (F) runoff.

Multiple linear regression models were used to relate the percent of developed- turf and developed- non-turf land in each HUC-14 subbasin to TN and TP concentrations calculated for 2007 (which corresponds to the year of turf analysis) (table 13) to determine the relative importance of developed- turf and developed- non-turf land in contributing nutrients to the estuary. The best-fit regression equations for relating the calculated 2007 TN and TP concentrations to turf are (table 17):

[TN] = 0.449 + 0.0135(T) + 0.0076 (NT) and [TP] = 0.0180 + 0.0012(T) + 0.0003(NT)

Where,

[TN] = predicted TN concentration, in mg/L

[TP] = predicted TP concentration, in mg/L

T = percent developed- turf

NT = percent developed- non-turf

As indicated by the r^2 values (table 17), not all variability in TN and TP concentrations is explained by the variability in percentages of developed- turf and developed- non-turf land. However, concentrations of TN and TP are accurately predicted at the watershed and segments scales using the regression equations. At the watershed scale, the TN concentration was 0.75 mg/L as N when calculated from both the regression equation and from concentrations at the HUC-14 scale determined from water-quality and hydrologic data; for TP, the calculated concentration was 0.035 mg/L as P using both methods (table 18). The regression relations predicted the mean concentrations of TN and TP in each HUC-14 reasonably well, with average absolute error of 20% and 32%, respectively. When analyzed by watershed segment, the TN concentrations calculated from the regression equation were 0.83, 0.61, and 0.64 mg/L as N for the north, central and south segments respectively. Total phosphorus concentrations were 0.040, 0.027 and 0.028 mg/L as P for the three segments. These values are similar to those obtained from runoff and baseflow water-quality data (±13%) (table 18).

The values of the regression coefficients indicate the relative influence of the land-use categories on nutrient concentrations. For both TN and TP, the coefficients for developed- turf are substantially greater than those for developed- non-turf land, indicating that areas with turf cover proportionally contribute a greater fraction of TN and TP than developed areas without turf cover. The regression models were used to predict concentrations for three single land-use scenarios for 2007: 100% undeveloped, developed- non-turf, and developed- turf (table 17). For TN, the predicted concentrations for a single land-use area is estimated to be 0.45 mg/L for undeveloped, 1.20 mg/L for developed- non-turf, and 1.80 mg/L as N for developed- turf. For TP, the predicted concentrations are 0.018 mg/L, 0.048 mg/L, and 0.138 mg/L as P for undeveloped, developed- non-turf, and developed- turf areas, respectively.

Although there are no single land-use areas in the BB-LEH watershed, this analysis provides evidence that developed areas contribute more nitrogen and phosphorus than less developed areas, and that developed- turf areas contribute more nitrogen and phosphorus than developed- non-turf areas. The higher TN and TP concentrations and loads associated with developed- turf areas are likely the result of fertilizer products being applied to lawns. The higher predicted nutrient concentrations in developed-non-turf areas compared to undeveloped areas shows that factors in addition to turf are contributing nutrient loads above background levels in developed areas.

Table 17. Multiple linear regression coefficients for relating percent of developed- non-turf, and developed- turf land in the Barnegat Bay-Little Egg Harbor watershed for 2007 to concentrations of total nitrogen and total phosphorus.

Table 18. Percent undeveloped, developed- turf, and developed- non-turf land (2007), and calculated concentrations of total nitrogen and total phosphorus, by watershed and watershed segment.

Summary and Conclusions

Concentrations, loads, and yields of total nitrogen (TN) and total phosphorus (TP) in the Barnegat Bay-Little Egg Harbor (BB-LEH) watershed were determined for years 1989-2011 from water-quality, hydrologic, land use, and precipitation data. Available surface-water quality data for streams in the BB-LEH watershed for 1980-2011 were compiled from the USGS's NWIS database and the USEPA's STORET database. Precipitation data were retrieved from the Office of the New Jersey State Climatologist and from the National Climatic Data Center. Daily mean discharge data for continuous streamflow gaging stations in the watershed were retrieved from the USGS's NWIS database, and GIS coverages of land use data for 1986, 1995, 2002, and 2007 were obtained from the New Jersey Department of Environmental Protection. These data were used to estimate surface-water loads of TN and TP for the BB-LEH estuary at a finer spatial and temporal scale than had been previously reported. Concentrations, loads, and yields were determined at three spatial scales: for each of the 81 subbasins specified by a 14-digit hydrologic unit codes (HUC-14s); for each of the three BB-LEH watershed segments; and for the entire BB-LEH watershed. The temporal scale was annual and seasonal (growing and nongrowing).

This BB-LEH watershed lies entirely in the Atlantic Coastal Plain physiographic province, and includes the drainage basins of numerous streams and tributaries that discharge to the BB-LEH estuary.

The watershed was divided into three segments—north, central, and south—to coincide with the natural segmentation of the estuary. The north segment is the largest (801.4 km^2), the most developed, and contains the drainage basins for the Metedeconk and Toms Rivers. The central segment covers 351.6 km^2, is the least developed, and contains the drainage basins for Cedar Creek, Forked River, and Oyster Creek. The south segment is the smallest (291.6 km^2) and contains the drainage basins for Mill Creek, Cedar Run, Westecunk Creek, and Tuckerton Creek.

Baseflow separation of hydrographs of six streams in the BB-LEH watershed indicated that baseflow accounts for about 65-90 percent of total flow in streams in the watershed. The baseflow-domination of the stream hydrology is characteristic of the flat terrain and highly permeable, sandy soil in the watershed. Baseflow accounts for a smaller percentage of flow in the highly developed basins, and a higher percentage of flow in the less developed basins.

Concentrations, loads, and yields of nutrients were calculated at the HUC-14 scale on an annual and seasonal basis with the use of available water-quality data and relations between concentrations and land-use percentages. Base-flow and runoff loading were calculated separately. For base flow, multiple linear regression models were used to determine relations between TN and TP concentrations measured at sampling stations during base flow, and land use in the contributing basins. These relations were applied to the land-use percentages of each HUC-14 subbasin to obtain calculated base-flow concentrations for each subbasin. Baseflow loads were then calculated as the product of the calculated concentration and base flow. For runoff, flow-weighted event-mean concentrations (EMCs) were developed for each land-use type and season combination from relations between land use and measured runoff concentrations. The land-use EMCs, along with annual and seasonal precipitation amounts, and percent imperviousness associated with land-use types, were applied using PLOAD to obtain calculated runoff concentrations, loads, and yields, at the HUC-14 scale. Land-use EMCs were greater during the growing season than the non-growing season.

Based on an evaluation of available surface-water quality data, the median concentrations of TN (0.79 mg/L) and TP (0.030 mg/L) were greatest in the north segment. Median concentrations were significantly less in the central (0.23 mg/L, TN and <0.010, TP) and south (0.31 mg/L, TN and <0.015, TP) segments. Higher median concentrations of both TN and TP in the north segment are consistent with a greater percent of developed land (agricultural plus urban) in the north segment.

Over the period of study 1989-2011, total surface-water loads (base flow plus runoff loads) of TN for the entire BB-LEH watershed ranged from about 522,000 kg as N to 921,000 kg as N. For TP, total loads for the watershed ranged from 22,800 to 40,200 kg as P. A greater proportion of the total loads were from base flow (78.1 % for TN, 67.1 % for TP), which is consistent with the hydrologic record and the base-flow separation results. Total loads fluctuated depending on precipitation and hydrologic conditions and patterns. Loads also are a function of land use. Increases in the amount of developed land in the watershed over time, in conjunction with the strong relationship between developed land and higher nutrient concentrations indicate higher loads in more recent years can be attributed in part to increases in development in the watershed.

On average, the north segment accounted for about 65 percent of the annual TN and TP loads to the estuary. This high percentage can be attributed to a combination of factors: the north segment is more than twice the size of the central or south segments, accounts for more than 60 percent of the streamflow in the watershed, and contains higher proportions of agricultural, and urban lands, each of which are associated with greater mean concentrations than undeveloped land. The corresponding northern estuary segment is the smallest of the three estuary segments which may further contribute to elevated nutrient concentrations in the northern part of the estuary. HUC-14 subbasins with the highest yields of nutrients are primarily concentrated in the northern part of the watershed, and have the highest percentages of urban or agricultural land use. Subbasins with the lowest TN and TP yields are dominated by forest cover.

The objective of assessing the contributions of TN and TP from turf (lawn) coverage was addressed by first quantifying the aerial coverage of turf throughout the watershed, and relating the estimated concentrations, loads, and yields of TN and TP to developed land with and without turf. Turf coverage was quantified in the watershed, and the contribution of turf to TN and TP loads was evaluated. This analysis was conducted for 2007. There is a strong relationship between percent turf and percent developed land in the watershed, such that the percent or area of total developed land can be considered a reasonable predictor of the percent or area of developed- turf land in the watershed. There also is a strong relation between percent turf and runoff yields, particularly for TP. In the BB-LEH watershed, predicted concentrations of TN and TP were greater for developed- turf areas than for developed- non-turf areas, which in turn, were greater than those for undeveloped areas. The higher predicted nutrient concentrations in developed- non-turf areas compared to undeveloped areas shows that factors in addition to turf are contributing nutrient loads above background levels in developed areas. This preliminary turf assessment indicates that controlling nutrient loads attributable to lawn care may be an effective way to reduce total loads. Given that nutrient loading to the estuary is controlled by water quality (as determined largely by land use and surface activities) and by flow volume, the most effective strategies for reducing nutrient loads would include controlling development and activities such as the application of commercial fertilizers and management of storm water.

Much of the land in the southern portion of the watershed is protected from intense development. Based on previous investigations in the watershed, and the analysis of existing data as part of this study, future increases in development in the central and south segments will likely lead to higher concentrations and loads of nutrients in the streams located in those areas, thereby increasing nutrient inputs to the estuary.

With this analysis, nutrient loads for the BB-LEH watershed have been estimated on an annual and seasonal basis at the HUC-14 scale. A more complete understanding of nutrient cycling in the watershed could be achieved with the use of additional, targeted water-quality monitoring in conjunction with a watershed water-quality model that considers in-stream processes, shorter time steps, and that targets individual streams and reaches.

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